Altaeros Energies

Airborne Wind Turbine
2013 Flight Prototype
Test Summary

Loring Commerce Center
November 2013

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Contents

1 Introduction

In November of 2013, Altaeros Energies tested a flight prototype designed to demonstrate stable operation in significantly stronger wind speeds than those seen by its 2012 functional prototype. This report summarizes the results of these flight tests.

1.1 Project description

The Altaeros Buoyant Airborne Turbine (BAT) uses an inflatable helium-filled shell to elevate a horizontal-axis turbine to high altitudes. A system of tethers connects the inflatable shell and turbine to a base station and transmits electricity between the base station and airborne system. The BAT is rapidly deployable and can be set up without a crane or concrete foundation. At altitudes of 100 to 600 meters above ground level, the BAT harnesses stronger and more consistent winds than those reached by tower-mounted wind turbines. The target market is remote military, industrial, community, and offshore applications powered by expensive diesel generators today. The technology is adapted from tethered aerostats, large tethered lifting balloons that have been used for decades to lift surveillance and telecom payloads into the air.

In 2012, the Altaeros team launched its first functional prototype, which integrated the Southwest Skystream 3.7, a popular off-the shelf residential turbine, into a custom-designed and manufactured aerostat platform. The team tested this prototype over a period of 2 months, demonstrating an initial proof of concept. While the team successfully demonstrated its system at a fundamental level, the test flights were limited to relatively low wind speeds (sustained winds below 15mph and a maximum gust of 23mph) and low altitudes (no more than 200 ft under 10+mph winds, and a maximum altitude of 104m). Because production systems will need to operate in substantially harsher conditions, at higher altitudes, the team recently tested a flight prototype that was targeted to demonstrate just that.

The recent Altaeros prototype demonstrated stable flight in strong winds and at a high altitude for its small size (7m in length). Specifically, during the testing conducted in November, 2013, the team accomplished the following milestones:

- Stable deployment up to 150m above ground level under sustained 10-15mph winds (no further altitude increase was allowed due to FAA limitations);
- Stable operation at 100m above ground level under sustained 20-30mph winds with a maximum gust of 45mph;
- Successful operation in snow;
- Initial deployment of a wind tracking algorithm, which adjusts altitude to “hunt” for the ideal wind conditions.

This flight prototype also retained successful elements from Altaeros’ 2012 prototype, including its rotating docking station and autonomous landing system.

2 Experimental setup

2.1 Prototype component fabrication and final assembly

The Altaeros BAT proof-of-concept prototype is depicted in Figure 1. Each of the three main prototype components was fabricated off-site, and final assembly occurred at the arch hangar facility at the Loring Commerce Center:

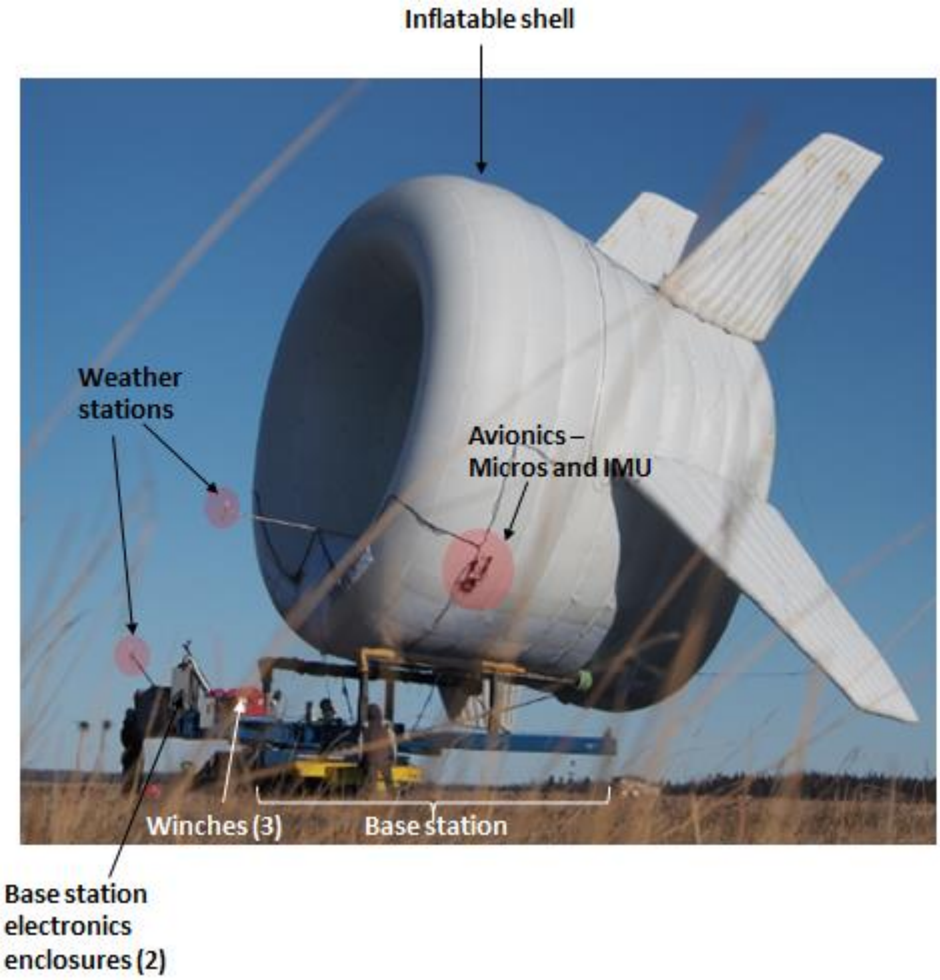

Figure 1 – Key components of the base station and inflatable shell.

- *Inflatable Shell:* The shell was fabricated by Cameron Balloons in Dexter, Michigan and incorporated a single layer of urethane coated nylon and several structural support layers around tether connections. The fins, which were also fabricated by Cameron Balloons, were constructed as separate, inflatable units and attached to the main shell via a set of guy lines and lashing patches.

- *Tethers:* The shell was tethered to a base station on the ground by 3 tethers, 2 of which were 1000ft-long ultra-high molecular weight polyethylene, and one of which was a high-strength conductive cable which served a dual purpose as a control tether and power link between the ground and shell.

- *Base Station:* The base station used for this prototype was based off of the 2012 base station but was retrofitted with a number of upgrades. The original single-speed winch controls were replaced with variable speed drives that allowed for continuously variable motion and substantially smoother operation.

2.2 Control, communications, and measurement system summary

The Altaeros BAT prototype employed a distributed sensor, communication, and control hardware setup, as visualized in Figure 2. This system consisted of 3 nodes:

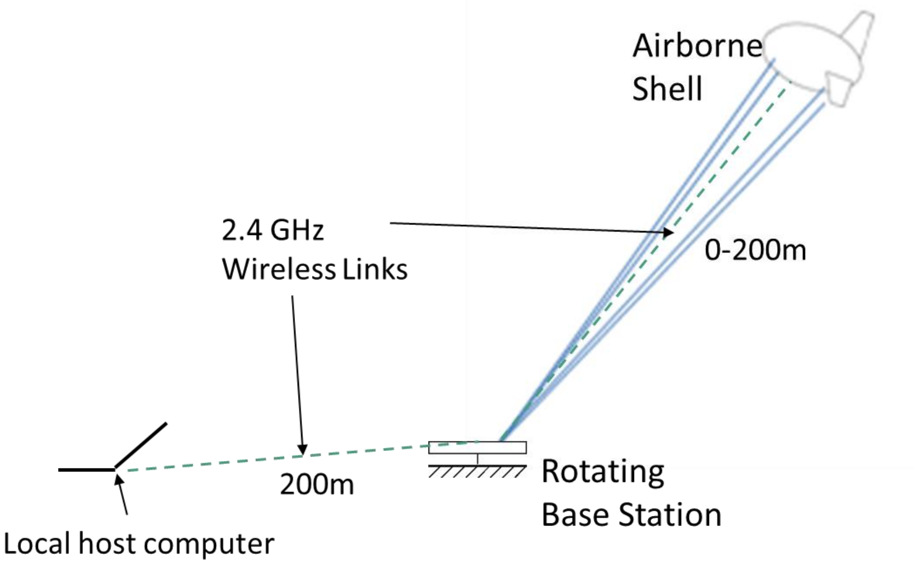

Figure 2 – Schematic of multi-node BAT control, communication, and sensor configuration.

- *Base station* – Housed the main controller, tether winches, and a slew drive for actively rotating the base station in low winds. The main controller aggregated sensor data and issued control commands to the winches and slew drive.
- *Inflatable shell* – Housed key airborne sensors and communicated sensor data down to the base station on a regular basis.
- *Host computer* – A remote PC that was located approximately 200m from the base station, equipped with a graphical user interface (GUI) for monitoring and issuing commands to the BAT. Telemetry data from the shell and base station were regularly relayed back to, and stored on, this host computer.

Example key components of the base station included:

- A 32 bit, 300 MHz microcontroller, which executes the main control algorithm;
- Ten 16-bit, 80 MHz satellite microcontrollers for digitally aggregating low-level data;
- A 2.4GHz wireless communication module and antenna;
- An all-purpose weather station, equipped with GPS and an ultrasonic anemometer;
- Three variable speed winches (5.6 and 3.8 kW, forward and aft, respectively) that regulate tether lengths for the purpose of attitude and altitude control;

Example key components of the inflatable shell and nacelle included:

- A 32 bit, 300 MHz microcontroller, aggregating and filtering airborne data;
- Three 16-bit, 80 MHz satellite microcontrollers for digitally aggregating low-level data;

- A 2.4GHz communication module and antenna;
- An all-purpose weather station, identical to that of the base station;
- Three pressure transducers, arranged to measure internal shell pressure;
- Two air compressors, designed to pump air into a ballonet and the fins.
- An emergency helium deflation system, triggered by excursions of over 1 mile from the initial deployed location.

The host computer was also equipped with a 2.4GHz wireless module, thereby completing the 3-node communication network.

2.3 Wind measurement details

Local wind measurement on the base station and inflatable shell was performed using the Airmar 150WX all-purpose weather station. The weather station is equipped with GPS, and provides both true and apparent wind speed. Wind measurements were internally filtered by the Airmar 150WX and communicated to the local 300MHz microcontroller at a 1Hz update rate, using the NMEA protocol over RS-422. The Airmar weather station wind speed measurements are accurate to within 0.5 m/s or 5% of the measured value, whichever is greater. This accuracy provides a reasonable basis for comparing simulated behavior with test data; however, a higher accuracy wind speed measurement will be sought for subsequent functional prototype testing, when the matching of power production the turbine's power curve becomes essential.

2.4 Testing and Permitting

All testing took place on the tarmac of the Loring Commerce Center airstrip, roughly 150m northwest of the Arch Hangar. The test site ground level was roughly 200m above mean sea level. During the prototype testing, Altaeros obtained the following regulatory approval:

- Certificate of Waiver from the Federal Aviation Administration (FAA) for operation of the BAT prototype up to 500 feet (approximately 150m) altitude above ground level during daylight hours for the duration of testing.

- Verbal confirmation from Fish & Wildlife Service (FWS) Maine office that the BAT prototype would have limited or no avian or animal impact. This finding was confirmed by a preliminary environmental assessment from Normandeau Associates.

3 Transient flight performance data

Following flight testing, performance data was compared with the predictions from Altaeros' dynamic model, using wind speed and direction data as inputs to the model. The team found that the airborne shell consistently pointed into the wind under all wind conditions, representing a marked improvement over Altaeros' previous design, which did not properly align itself with the wind under wind speeds exceeding approximately 6 m/s (13 mph). Figures 3 and 4 demonstrate this alignment under light-to-moderate (November 21) and moderate-to-strong (November 23) wind conditions. The team also found that its dynamic model, which was refined between the last round of testing and the present round, provided an accurate prediction of the system behavior under most circumstances.

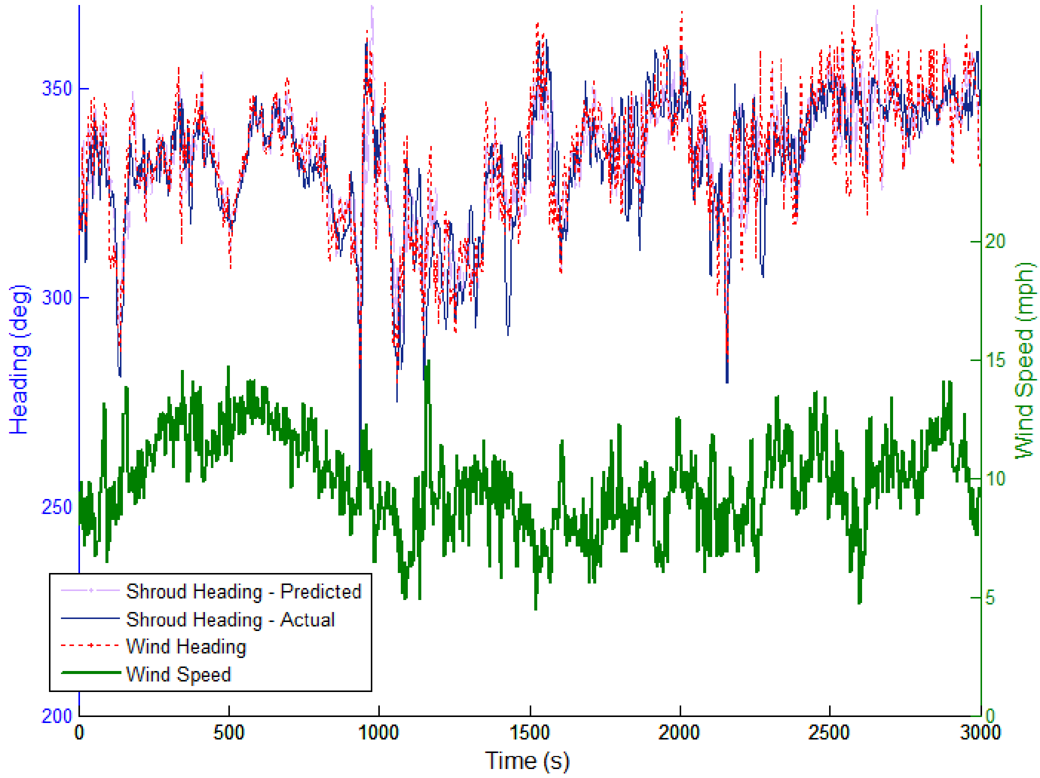

Figure 3 – Sample flight test data from November 21, 2013, indicating accurate tracking of wind heading under light to moderate sustained winds of 5-15 mph.

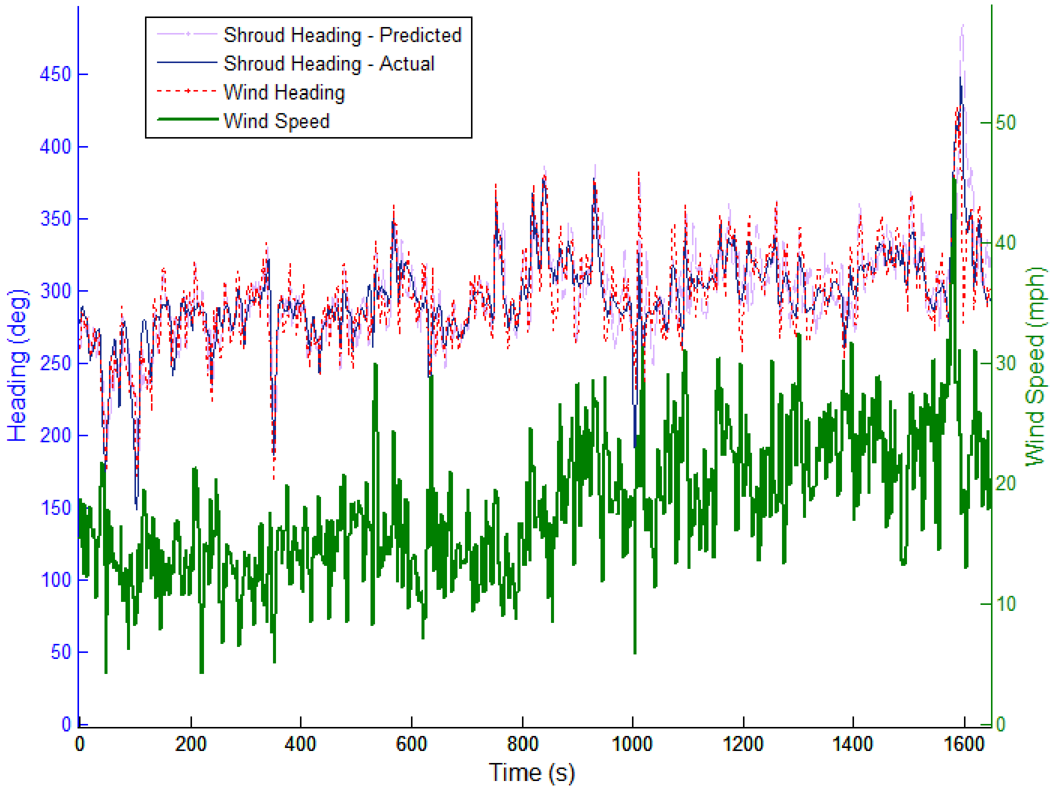

Figure 4 – Sample flight test data from November 23, 2013, indicating accurate tracking of wind heading under 20-30mph sustained winds (toward the end of the plot window) and a 45mph gust (the maximum instantaneous gust seen over the test duration).

3.1 Discussion

Flight test results indicate that the BAT prototype fulfilled its most fundamental objective: to point into the wind quickly and consistently under a representative range of wind speeds. Test results can be analysed further, however, in order to evaluate Altaeros' design methodology and to identify areas for the team to focus its attention on moving forward.

Implications of test results on design methodology:

In terms of its design methodology, Altaeros employs a "four-quadrant" design approach, depicted in Figure 5, which incorporates simulation and experimental components in both a steady-state and dynamic framework. Altaeros' steady-state design tools include CFD software (using Realizable k-ε turbulence models) and wind tunnel validation in the University of Michigan 5x7ft subsonic tunnel. The team's dynamic modelling tools include two in-flight dynamic models (one lower-fidelity model that treats tethers as kinematic constraints and a higher-fidelity model that considers tether dynamics), developed in-house using MATLAB and Simulink, and a water channel platform, developed in conjunction with the University of Michigan, that is used to evaluate flight dynamics on ABS plastic shell models.

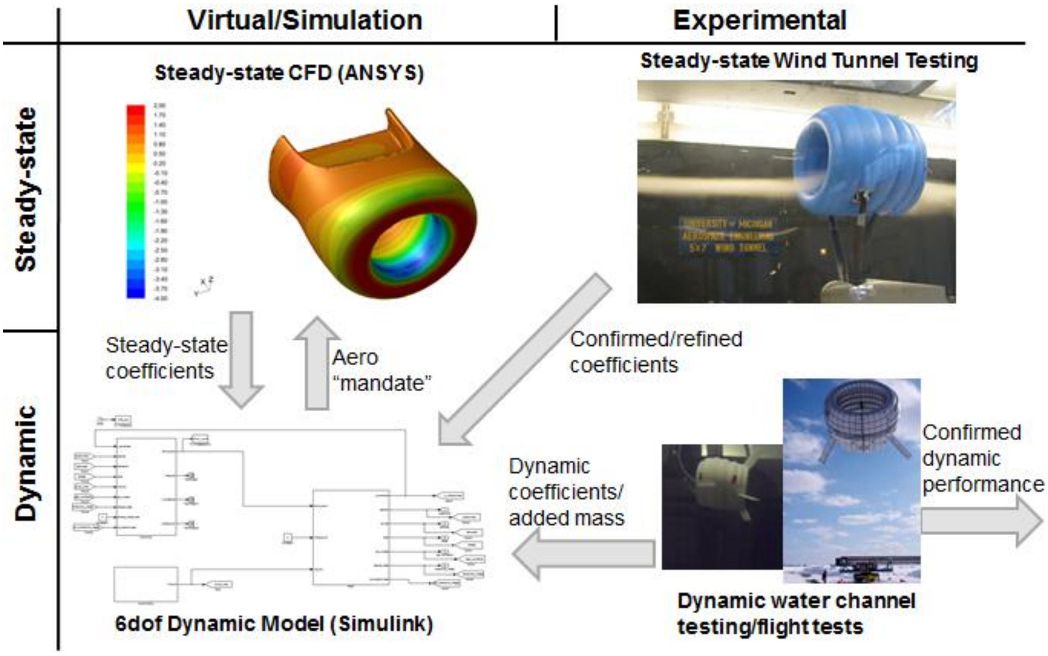

Figure 5 – Diagram of Altaeros' 4-quadrant design and analysis approach

While it is difficult to find a wind tunnel that would accommodate the full-scale prototype, the accuracy of aerodynamic coefficients can be reasonably confirmed by the comparison of tether tensions against the values predicted by the dynamic model. Such a comparison, as shown in Figure 6, indicates that the model predicts similar steady-state tensions to those seen in the data. This bodes well in terms of validating our steady-state aerodynamic modelling approach. On the other hand, tension predictions exhibit significant transient oscillations, indicating that our higher-fidelity, tether dynamics model still has not yet reached a point where it can predict transient tether tension variations reliably.

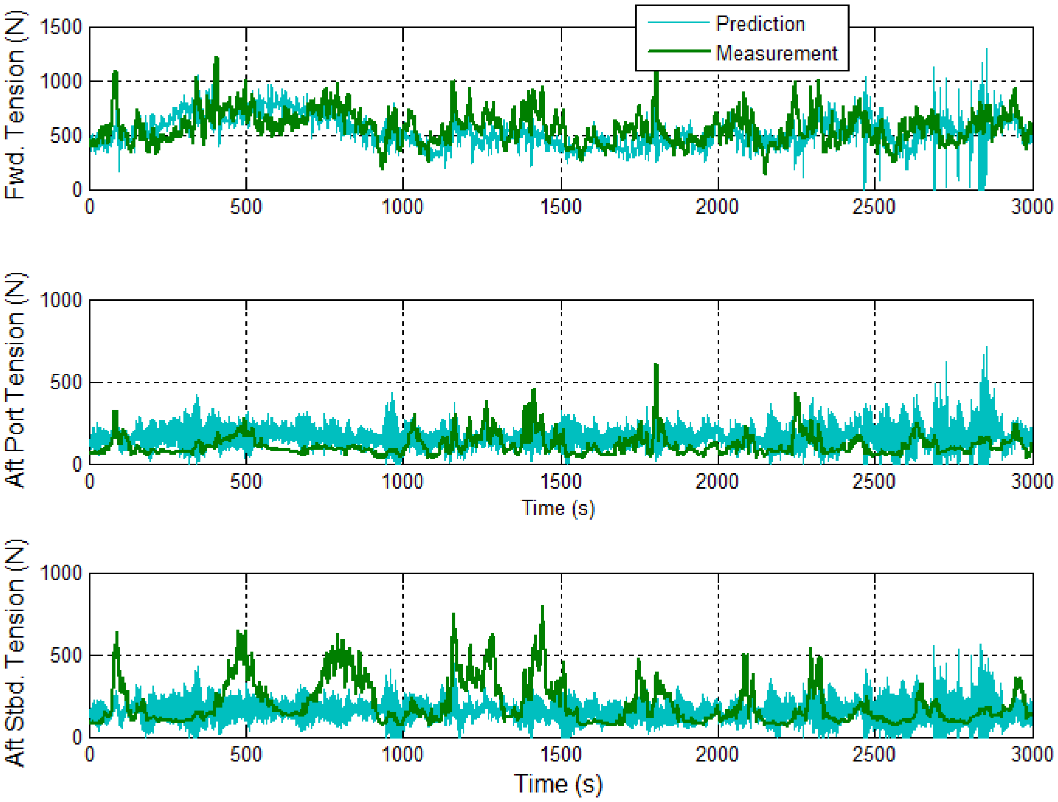

Figure 6 – Sample tether tension data, in comparison to model predictions.

One of the largest changes in design approach between Altaeros' 2012 and 2013 prototypes was the inclusion of a lab-scale experimental component in the form of water channel testing. Photographs of the test-rig are shown in Figure 7; here, ABS plastic models were tethered to the base of the University of Michigan 2ft x 2ft water channel, and cameras recorded the models' motion under different flow speeds.

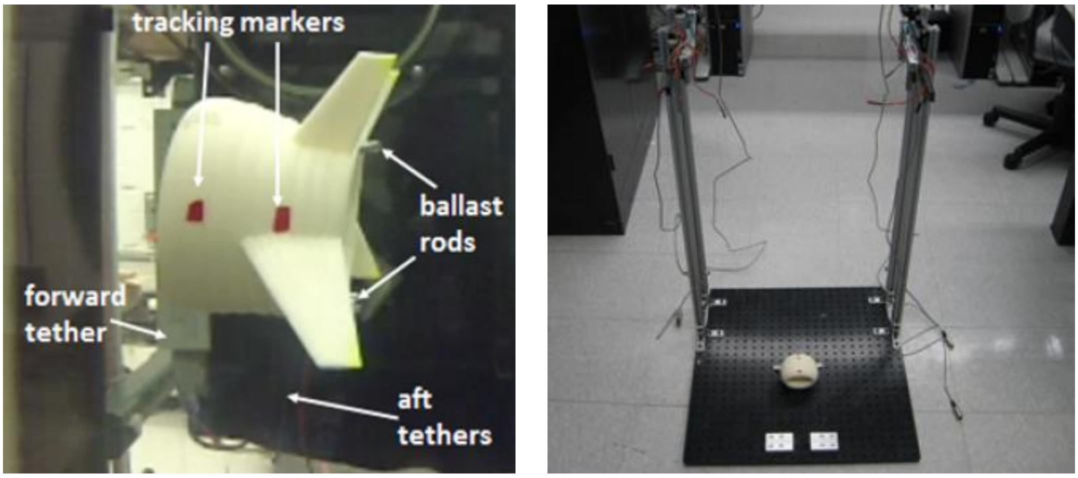

Figure 7 – Images of water channel testing in progress (left) and the test rig outside of the channel (right)

Table 2 descriptively compares the simulated and experimental (both water channel and full-scale) dynamic performance of the BAT under a number of ballasting (center of mass) configurations. Results indicate alignment between the water channel and simulation model and also indicate that the water channel accurately predicts trends in dynamic performance. Because several ballasting configurations led to highly undesirable behavior in the water channel, the team did not take on the risk of testing these configurations on the full-scale system, as they would have likely led to failure.

Ballast Configuration #	Simulation	Water channel	Flight tests
1	Unstable	Unstable	Did not test
2	Stable	Oscillatory or skewed	Did not test
3	Stable	Stable	Oscillatory or skewed
4	Stable	Did not test	Stable, sometimes skewed
5	Stable	Stable	Stable

Table 2 – Comparison of dynamic performance between the dynamic model, water channel, and flight tests.

Not only was the water channel an accurate indicator of design trends, but the use of this platform helped to confirm a design strategy that was initially counterintuitive and would not have likely been attempted on the full-scale model without this small-scale experimental platform to back up the judgment.

Areas to improve:

While flight testing identified some strong points in our design methodology, it also identified some areas that require improvement before attempting operation for very long durations (i.e. weeks or months at a time) and in higher wind speeds above the 45 mph encountered in this round of testing.

One area for improvement, mentioned earlier, lies in fixing the tether dynamics model to more accurately predict transient variations in tether tension. Because the tether dynamics possess much higher natural frequencies than the aerodynamic components of the system, the inclusion of the tethers in the dynamic model stiffens the system and makes it inherently difficult to simulate using differential equation solvers. However, this system is not alone in the presence of frequency-scale separation, and future work will leverage modelling techniques from similar systems to improve the handling of tether tensions in the Altaeros model.

Another area for improvement lies in the area of designing a more nimble controller that responds quickly to small excursions in pitch, roll, or altitude (especially pitch and roll, as excursions in the former can result in stall and excursions in the latter can result in significant lateral deviations that cannot be immediately reacted by tethers). From Figure 8, one can see that with present control parameters, roll and pitch angles routinely deviated by 5 or more degrees from their setpoints, and in one strong-wind occasion the roll angle deviated by 40 degrees, which triggered the team to initiate a descent. While these deviations are also seen in simulated behavior, it is important that they be reduced for subsequent tests.

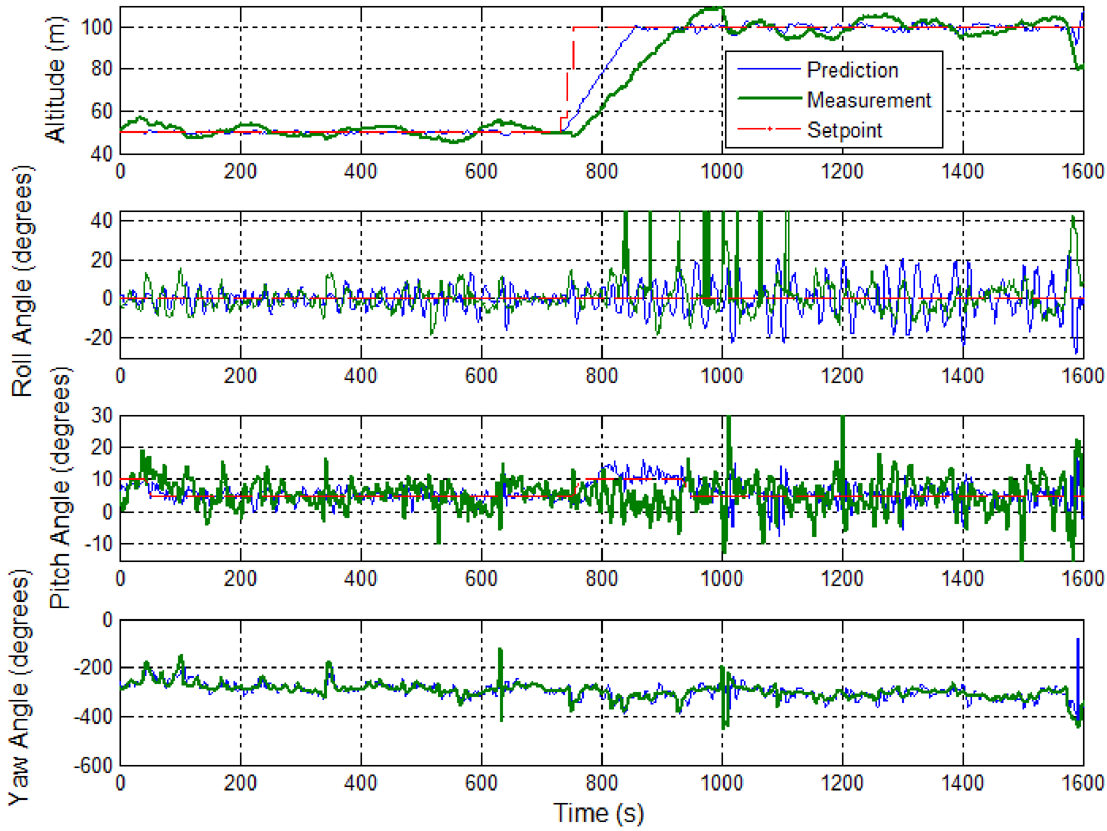

Figure 8 – Altitude and attitude under strong winds experienced on November 23, 2013. Note, the spikes in roll angle between 850s and 1100s are a result of communications errors, not actual measurements.

4 Conclusions

This report has described the experimental setup for the Altaeros' 2013 BAT flight prototype and presented quantitative performance results. Broadly speaking, the following conclusions may be drawn from performance data:

- The prototype successfully demonstrated passive alignment with the wind in wind speeds up to 20.3 m/s (45 mph). Validation of the design in even stronger winds remains a topic for future investigation.
- The prototype was flown to 150m (495ft) above ground level.
- From initial flight test results, it became clear that the control gains needed to be adjusted (detuned) in order to avoid oscillatory behavior and resulting controller-induced instability. Reducing control gains resulted in stable flight behavior but also sometimes resulted in substantial deviations between altitude/attitude and their setpoints.
- Flight test behavior very closely matched the behavior that was observed in lab-scale water channel models. Flight behavior also generally matched simulation results.